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Evaluating the challenges associated with the long-term reliable operation of industrial wind turbine gearboxes

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Abstract

Wind turbine gearboxes are required to operate under adverse operational conditions over a long service lifetime. Unfortunately, gearbox designers are yet to achieve the reliability anticipated by wind turbine manufacturers and operators. The poor understanding of variable loading conditions has resulted in the majority of wind turbine gearboxes being unable to reach their expected service lifetime of 20-25 years. This has led to an increasing need to investigate the fundamental issues associated with the degradation of wind turbine gearbox materials during operation in order to improve existing designs and optimise future ones. This paper investigates the various challenges that need to be addressed in order to achieve a noteworthy increase in the operational service lifetime of large-scale industrial wind turbine gearboxes.

1. Introduction

Over the last decade, the global wind power capacity was steadily growing at an annual rate of around 23%, becoming the most important renewable energy source on a global scale [1]. At the same time, the rated power capacity of wind turbines has greatly increased from 15 kW in the 1980s to around 9.5 MW in 2015 (VESTAS V-164 model). To enable the production of higher power output the diameter of the rotor has increased as well, reaching currently a maximum of 164 metres. Historical trends imply that power capacity and size of wind turbines will keep increasing with the construction of 20 MW models being quite possible in the mid-term future [2]. However, the expansion of wind power capacity has been restricted due to a number of operational challenges which are yet to be addressed. The most important of these challenges appear to be the reliability of the wind turbine gearboxes. Wind turbine gearboxes are currently unable to survive their predicted design lifetime of 20-25 years. Most of them hardly reach a useful operational lifetime of more than 7 years without serious refurbishment or replacement. In offshore wind turbines, failure occurs even earlier due to the highly variable loads experienced by these turbines. Gearbox failures tend to be either related to gear or bearing failures although shaft related defects occur also. In the UK, it is estimated that 20% of the Levelised Cost of Electricity (LCOE) produced by offshore wind farms arises due to operation and repairs [3].

Approximately 75% of all commercial wind turbines employs three-stage gearboxes, combining parallel, helical or spur gears together with planetary gears. Wind turbines convert rotor torque to electrical power by employing a speed multiplier gearbox and an induction generator. The gearbox increases the turbine shaft rotational speed to the speed required for the generator to produce power while reducing torque by the same ratio. The conditions in which wind turbine gearboxes operate are different from other gearboxes used in conventional steady-state applications. The loads



under which they are submitted vary with the aerodynamic torque applied on the blades. There are also other external electromechanical failures that can generate shock loads, as well as lateral loads that can be transferred to the gearbox. The lack of satisfactory understanding of the stochastic and cyclic loads, as well as misalignment of the high-speed shafts and lack of proper lubrication, are some of the causes of the gearboxes premature failure, whilst failure mechanics are not fully understood yet [4- 5].

Numerous authors believe that the leading factor of wind turbine gearbox failures is due to bearing damage which can subsequently progress into the gear teeth as excess clearance and wear debris, producing misalignment and surface wear [6-8]. A study by Kotzalas and Doll [9] has concluded that the wear suffered by the main bearings reduces its lifetime, leading to downtime up to 600h [8], mainly due to the difficulty associated with access to the nacelle as well as access to the wind farm site itself [10-11]. The replacement of a gearbox can result in significant expenditure, excluding the costs of hiring crew and cranes needed for the replacement, and lost energy production.

2. Gearbox materials and types of failure

Ferrous alloys are usually the designer's first choice when it comes to power transmission gears [12]. Gears for this kind of application generally use high Cr steel that has a soft and tough core, in order to accommodate the bending on the basis of the gear tooth [13]. Table 1 shows data on different materials and treatments used for gear design.

Table 1. Material data for gear design. Adapted from [14].

| Condition or treatment | Material | Surface hardness (HV) | Tensile strength of core (MN/m ²) | Allowable contact fatigue stress (MN/m ²) | Allowable bending fatigue stress (MN/m ²)* |
|------------------------|------------------------------|-----------------------|---|---|--|
| Normalised | 0.4% C steel | 165 | 530 | 10 | 145 |
| Through hardened | C-Mn, Mn-Mo, 3% Ni | 200 | 695 | 12.5 | 159 |
| | 1% Cr-Mo, 3% Ni-Cr, 3% Cr-Mo | 250 | 850 | 21.5 | 214 |
| | 1% Cr-Mo, 2.5% Ni-Cr-Mo | 270 | 925 | 23.5 | 221 |
| | 3% Ni-Cr-Mo | 365 | 1230 | 26 | 234 |
| Carburised | C case hardening steels | 800 | 495 | 65.5 | 214 |
| | 2% Ni-Mo | 725 | 750 | 69 | 255 |
| | 3% Ni-Cr-Mo | 750 | 950 | 75.5 | 283 |
| | 4.25% Ni-Cr, 4.15% Ni-Cr-Mo | 710 | 1250 | 89.5 | 345 |
| Nitrided | 3% Cr-Mo | 850 | 800 | 55 | 179 |
| | 3% Cr-Mo-V | 850 | 1250 | 69 | 283 |

*These values do not include stress concentration factors at the tooth roots.

The most usual failures experienced by wind turbine gearboxes are gear tooth and bearing damage, as well as broken shaft and high oil temperature. Bearing failures, as discussed earlier, are found to be the root cause of the majority of these failures, mostly due to micro-pitting, scuffing, false brinelling, and fretting corrosion [15-16]. Contamination in the gearbox oil is a problem that has been investigated in numerous studies. Particle contamination can cause abrasive wear and initiate surface fatigue spalling, as well as reduce the service life of gear lubricants [9, 15]. Impurities are capable of entering the gearbox during manufacturing, assembly or maintenance, produced by wear, or admitted by breathers and seals. The use of smooth surfaces, surface-hardened gears and high viscosity lubricants can minimise the internal generation of wear debris [16]. Due to variable loading, gearbox components are also subject to instant and long-term misalignments of the gear mesh, as well as bending of the gearbox casings and shafts [9].

3. Condition monitoring of the gearbox

Condition monitoring systems are used to verify the condition and quantify the reliability of an in-service system. The main concept behind condition monitoring is to choose a quantifiable parameter on the device that will vary as the condition of the device or component deteriorates. By monitoring this parameter, it is possible to detect a change and then make a more detailed analysis in order to reach a diagnosis [17]. In the early days, industrial wind turbines were only monitored during regular inspections carried out by maintenance personnel attending them. However, in order to realistically reduce the breakdown rate more effective inspection procedures based on the efficient use of remote condition monitoring had to be implemented. The application of remote condition monitoring systems aims to identify faults as early as possible, preventing the likelihood of catastrophic failure and unnecessary loss of production, and consequently define repairs in time [18]. As wind turbines became larger and more expensive, the need to monitor their performance and foresee damage initiation and rate of propagation has increased. Hence, remote condition monitoring systems have become standard in order to improve the protection of these expensive assets and maximise the potential of wind energy by reducing downtime and maximising availability and hence capacity factor [19].

Remote condition monitoring systems are installed on the drive-train, in order to determine the actual condition of its sub-components (main bearing, gearbox components, generator bearings). Currently, vibration analysis is the most popular technique for monitoring onshore and offshore wind turbines [20-23]. It is important to notice that the capability of remote condition monitoring systems relies both on the number and type of sensors, as well as the extraction and analysis methods [18]. Industrial wind farms incorporate supervisory control and data acquisition (SCADA) systems that are responsible for connecting the wind farm and meteorological stations at the wind farm site to the dispatch centre of the wind farm operator. These systems are used to monitor a number of parameters including bearing temperature and vibration of the drive-train.

Degradation or damage to the gearbox may manifest in several forms, such as debris, vibration, additional heating or acoustic emission. Therefore, vibration analysis, oil debris analysis and acoustic emission monitoring can be used to effectively monitor the gearbox condition [24]. It is noteworthy to mention at this point that no single technique can detect all possible failure modes since each has its own strengths and limitations [25].

4. Surface engineering

Gear failures characterised by superficial flaws are common and intricate, due to the contact fatigue occurrence involving the gear and the loading conditions produced. In order to achieve a long lifetime, gears must have a tough core in order to withstand fatigue bending and impact stresses, as well as hard surface and fatigue strength to reduce the damage caused by wear and sub-superficial cyclic loading, respectively. It is possible to achieve such versatile mechanical properties by employing appropriate effective surface treatment processes, such as carburising and nitriding. Both surface treatment methods generate residual compressive stresses in the most superficial layers, increasing the endurance limit for cyclic stresses [26]. Duplex surface engineering is also an alternative way of achieving the required properties by combining two or more surface treatment processes.

5. Finite element modelling

In this work, the commercial finite element (FE) software ABAQUS/Standard by 3DS SIMULIA has been used to simulate the meshing gears in a wind turbine gearbox. The gears were designed in the CAD software Solidworks and imported to ABAQUS. Their specification is given in Table2.

Table 2. Gear pair specification.

| Gear parameter | Values | Unity |
|---|--------|---------|
| Module (m) | 2 | mm |
| Number of teeth of the pinion (N_p) | 34 | - |
| Number of teeth of the gear (N_g) | 34 | - |
| Pitch radius of the pinion (d_p) | 68 | mm |
| Pitch radius of the gear (d_g) | 68 | mm |
| Face width (F) | 20 | mm |
| Pressure angle (ϕ) | 20 | degrees |
| Addendum (a) | 2 | mm |
| Dedendum (b) | 2.5 | mm |
| Root fillet radius (rf) | 0.6 | mm |
| Clearance (c) | 0.5 | mm |

The material chosen for the simulation was the 18CrNiMo7-6 steel since it is used in the wind turbine gear industry [27]. In the model, the following material properties have been employed as shown in Table 3.

Table 3. Material properties used in the FE model. Source: [28]

| Material property | Value |
|-----------------------|-------|
| Young's modulus (GPa) | 210 |
| Poisson's ratio | 0.29 |

Subsequently, the gears were cut and only three teeth on each gear remained. This was done in order to simplify the model and save on computational resources, as shown in Figure 1. Finally, the boundary conditions are defined in the model. Table 4 summarises the boundary conditions applied.

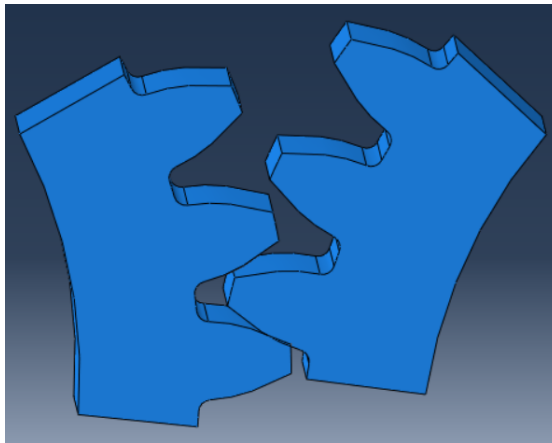
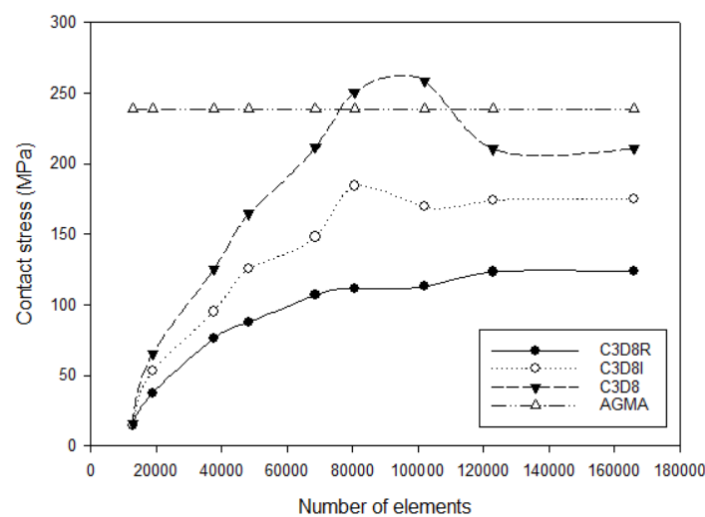
**Figure 1.** Final design of spur gear pair for ABAQUS simulation, isometric view.

Table 4. Summary of the boundary conditions applied to the gear pair.

| Boundary condition | Pinion | Gear |
|--------------------------|--------|------|
| U1 | 0 | 0 |
| U2 | 0 | 0 |
| U3 | 0 | 0 |
| UR1 | 0 | 0 |
| UR2 | 0 | 0 |
| UR3 | Free | Free |
| Torque (N/mm) | 5000 | 0 |
| Angular velocity (rad/s) | 0 | 1.8 |

A mesh convergence analysis was performed and the model was found to converge at around 120 thousand elements, to three different element types, as shown in Figure 2.

**Figure 2.** Contact stress mesh convergence analysis for the gear pair.**Table 5** Variables and descriptions for the AGMA contact stress equation.

| Variable | Description |
|------------|---|
| σ_c | Contact stress (MPa) |
| Z_E | Elastic coefficient ($\sqrt{\text{MPa}}$) |
| W_t | Tangential transmitted load |
| K_o | Overload factor |
| K_v | Dynamic factor |
| K_s | Size factor |
| K_H | Load distribution factor |
| Z_R | Surface condition factor |
| d_p | Pitch diameter of the pinion (mm) |
| F | Face width (mm) |
| Z_I | Geometry factor for pitting resistance |

6. Results and discussion

A fundamental stress equation for contact stress of gears (also called pitting resistance equation) was developed by AGMA and is shown in **Error! Reference source not found.** [29]. This equation has been used to compare and validate the data obtained from the finite element model.

$$\sigma_c = Z_E \sqrt{\frac{W_t K_o K_v K_s K_H Z_R}{d_p F Z_I}} \quad \text{Equation 1}$$

A description of each variable is given in

Table . A more detailed explanation of each variable can be found in [29-30].

By using **Error! Reference source not found.** and the summarised data from Table 6, one can calculate the AGMA contact stress for this gear pair being 239.45 MPa.

Table 6. Summarised variable data for the evaluation of Eq. 1.

| Variable | Value | Unit |
|----------|--------|--------------|
| Z_E | 191.65 | \sqrt{MPa} |
| W_t | 147.06 | N |
| K_o | 1 | - |
| K_v | 1 | - |
| K_s | 1 | - |
| K_H | 1.16 | - |
| Z_R | 1 | - |
| d_p | 68 | mm |
| F | 20 | mm |
| Z_I | 0.08 | - |

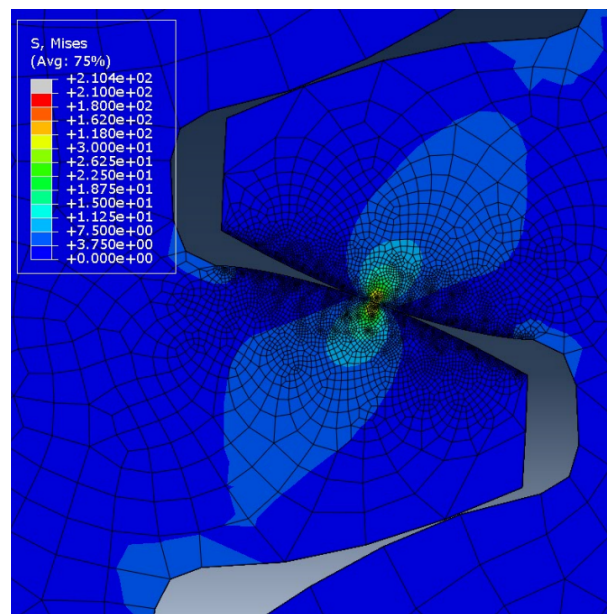


Figure 3. Von Mises contour plot of gear pair, front view.

It is now possible to compare the AGMA values with the results obtained from the mesh convergence analysis. The comparison between the AGMA and FE results is shown in Table 7. It is possible to see that the C3D8 element yielded by far the best results on the contact stress analysis, with 12.13% error. These results are in line with the results obtained by Wright [31].

Table 7. Comparison between FE and AGMA results.

| Type of element | Contact stress | | |
|-----------------|----------------|--------|--------|
| | FE | AGMA | Error |
| C3D8R | 123.2 | 239.45 | 48.55% |
| C3D8I | 174.1 | 239.45 | 27.29% |
| C3D8 | 210.4 | 239.45 | 12.13% |

Finite element analysis can be used to calculate the exact location of the highest Von Mises stress, as well as display the values of Von Mises for the entire model, in the form of contour plots. For the validated gear pair made from C3D8 elements from the previous section, the contour plot of the Von Mises stress is shown in figure 3.

7. Conclusions

The present study presents an overview of the factors influencing degradation of gearboxes in wind turbines along with methodologies typically used to monitor their condition. The use of remote condition monitoring systems offers valuable diagnostic insight but the prediction of failure involves considerable challenges that are yet to be addressed. A plausible approach in increasing the potential for prediction of degradation evolution in different gearbox should consider the use of finite element analysis studies coupled with detailed forensic analysis of failed components retrieved from the field. Predictive maintenance has the potential to reduce considerably the operational and maintenance costs of industrial wind turbines leading to cheaper electricity production for operators and hence cheaper electricity prices for consumers in the long-term helping accelerate the decarbonisation of the global economy without risking deceleration of economic growth.

8. Acknowledgements

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